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USE OF TIME DOMAIN REFLECTOMETRY

FOR

EMP HARDNESS SURVEILLANCE

By

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A laboratory demonstration of the feasibility of using a time domain reflectometer (TDR) to detect failures of electromagnetic pulse (EMP) hardening capacitors is described. The TDR enables a technician to easily detect an open circuit failure in a capacitor if measurements can be made near the capacitor. Measurements can also be made at a distance if previous measurements of a known good installation are available for comparison. The Tektronix 1502 TDR cable tester was found to be particularly well suited to making these measurements.

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Some of the measurements reported in section 5 were made with a Tektronix 1502 TDR Cable Tester loaned to MITRE by H. Payne of Tektronix.

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SECTION 1

INTRODUCTION

This paper addresses a hardening maintenance problem affecting electromagnetic pulse (EMP) hull hardened aircraft like the E-4B. Wires penetrating the pressure hull of the E-4B are typically hardened with capacitors or other low-pass filters which shunt high frequency signals, including EMP, to the pressure hull. If a filter fails in a short-circuit condition, the associated circuit fails and the failure will eventually be detected. However, if the filter fails in the open-circuit condition, there are no indications of the failure. Most electrical measurements to determine the presence of a capacitor to ground depend on knowledge of the wire terminations at both ends. However, a time domain reflectometer (TDR) can measure the impedance to ground as a function of distance along the wire. This paper describes a feasibility demonstration of this technique.

The second section of this paper describes the EMP hardening surveillance problem in more detail. Section 3 describes time domain reflectometry, and section 4 describes its proposed application to hardness surveillance. Section 5 describes the feasibility demonstration. Conclusions are listed in section 6.

SECTION 2

EMP HARDENING SURVEILLANCE

A typical electrical wire penetrating the pressure hull of the E-4B is hardened by means of a feed-through capacitor, usually .22 microfarad, between the wire and the hull. The distribution of types of hardening on the E-4B is shown in figure 1. The capacitor provides a low impedance path to ground for high frequency signals (one ohm or less above 1 MHz, for .22 microfarad). Since wires frequently penetrate the hull in crowded areas, the capacitors are placed in a separate filter box and the connecting wires shielded. The typical arrangement is shown in figure 2.

The predicted failure rates for EMP hardening components are indicated in figure 3. If a hull hardening capacitor fails in the short-circuit condition, the associated circuit will cease to function, and the problem will eventually be discovered. However, if the capacitor fails in the open-circuit condition, there are no indications of the failure. A technician trying to make electrical measurements at the filter is faced with the circuit in figure 4. Unless he knows the terminations at both ends of the wire, he is apparently forced to remove the capacitor from the circuit, check it, and reconnect it. Finally, he must functionally test the associated circuit to confirm that it is still working. While this procedure is straightforward and unambiguous, it can take a long time: it increases the risk of damage from handling, and can be difficult due to the poor accessibility of some filter boxes.

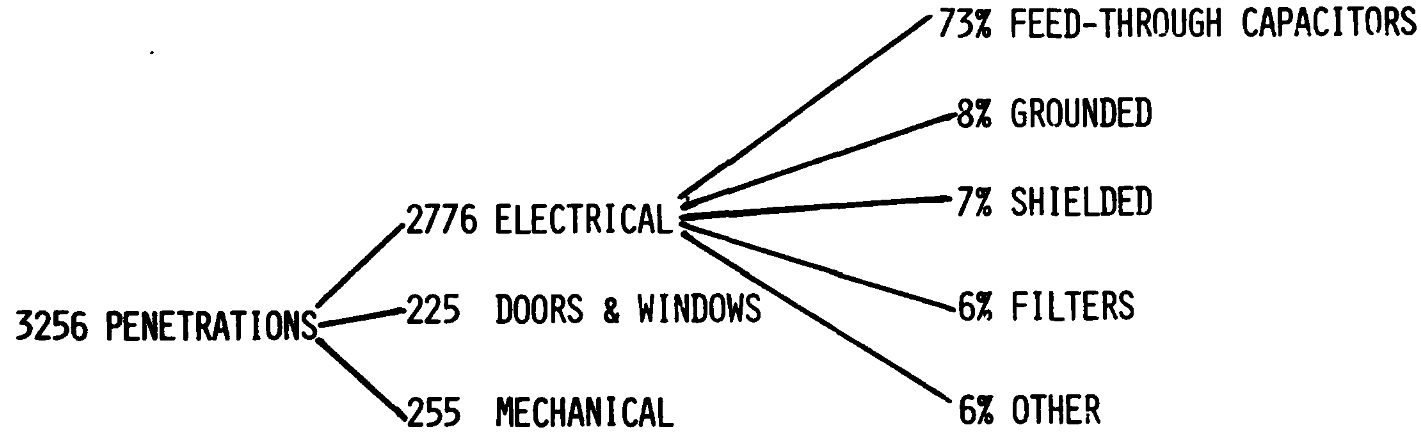


Figure 1. Types of EMP Hull Hardening on the E-4B

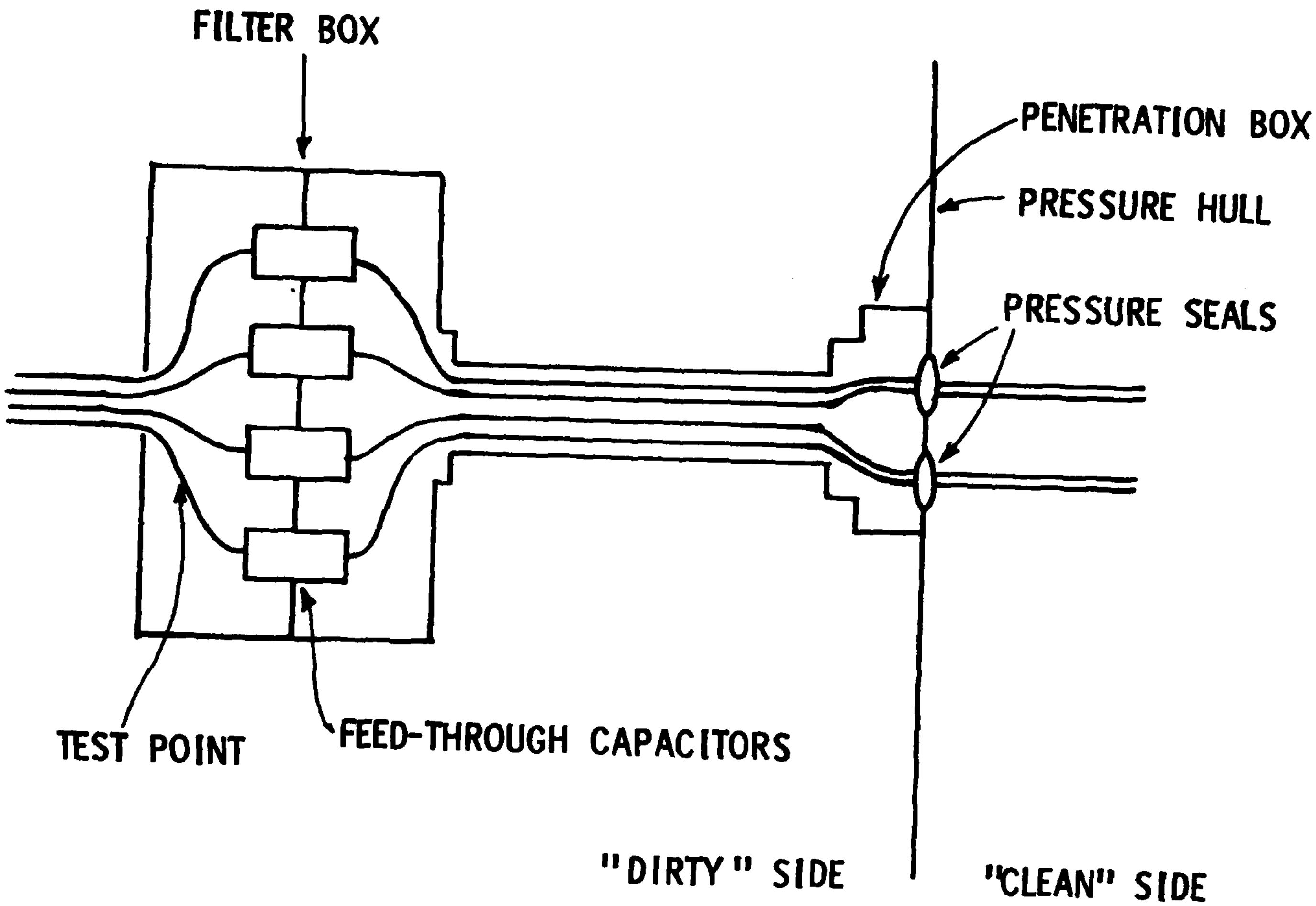


Figure 2. Typical EMP Hull Hardening Installation on the E-4B

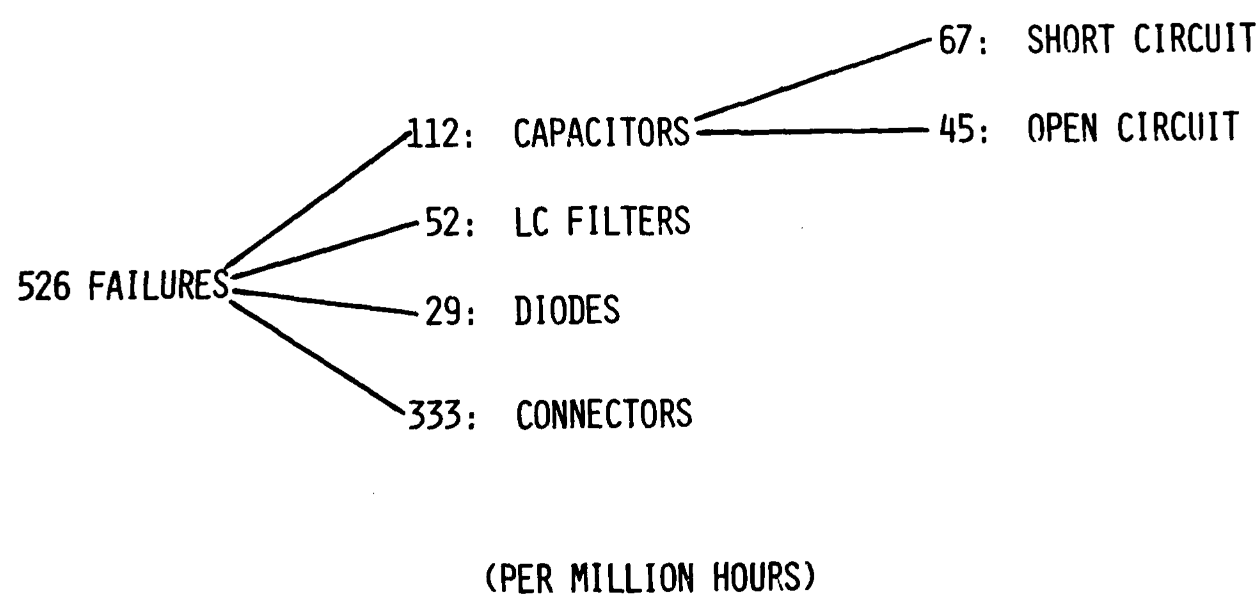


Figure 3. Predicted Failure Rates of E-4B EMP Hardening Components

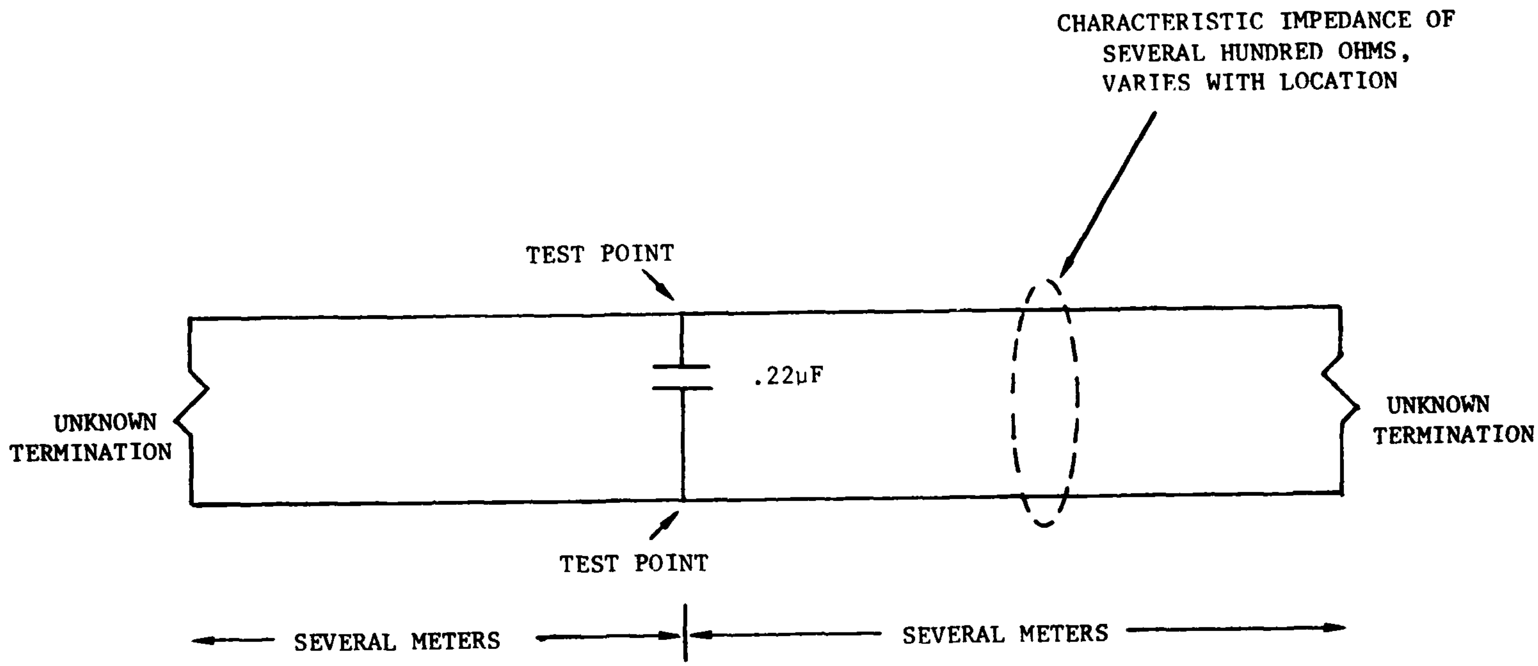


Figure 4. Circuit Diagram of a Typical Hardened Electrical Penetration

SECTION 3

TIME DOMAIN REFLECTOMETRY

Time domain reflectometers were developed to diagnose problems with high frequency transmission lines, and are used extensively in the maintenance of telephone cables. They operate in the same manner as radar, but use signals confined to a transmission line rather than radiated into free space. A traditional TDR applies a fast-rising voltage step across one end of the transmission line and displays the voltage at the drive point as a function of time. The voltage step propagates along the line until it encounters a change in the line's impedance. The interpretation of the TDR display is illustrated in figure 5. If the impedance increases, the reflection will cause the voltage at the drive point to increase after two transit times from the drive point to the impedance change. If the impedance decreases, the reflection will cause the voltage at the drive point to decrease. Reflections from greater distances will of course take more time to reach the drive point. Thus, the TDR's display of voltage as a function of time is nearly equivalent to a display of impedance as a function of distance. A series inductance (which has a high impedance at high frequencies) causes a voltage step followed by a gradual decay as the current builds up in the inductor. A shunt capacitance (which has a low impedance at high frequencies) causes a voltage decrease followed by a gradual rise as the capacitor charges up. Several impedance changes would cause multiple reflections and complicate the display. However, the first such discontinuity is still detected unambiguously. For a more complete discussion of TDRs, see Reference TEK76.

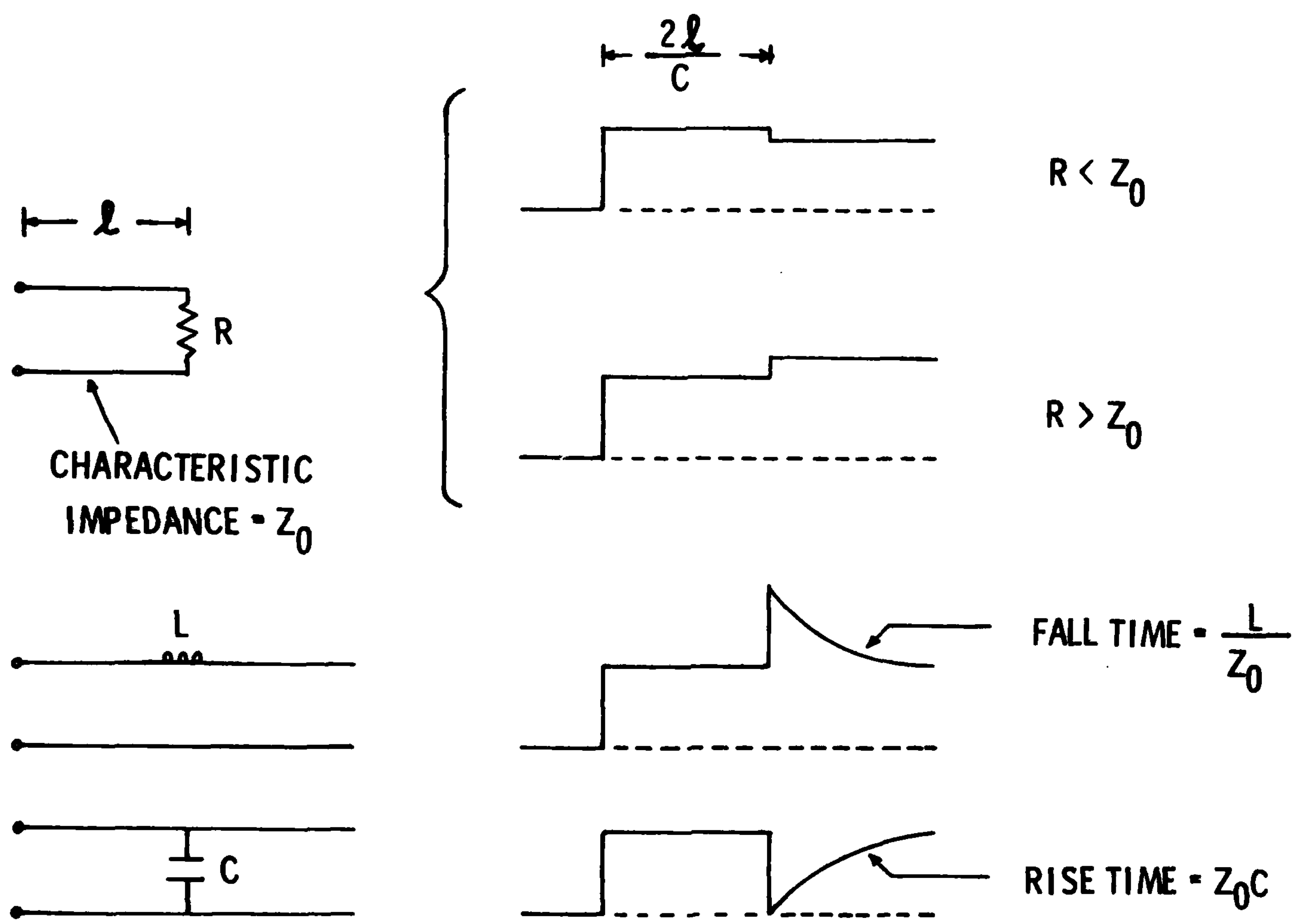


Figure 5. Interpretation of TDR Displays

SECTION 4

HARDNESS SURVEILLANCE USING A TDR

Since electrical wiring is routinely bundled and routed along the aircraft structure, any one wire can be viewed as a transmission line (wire over a ground plane). Of course, the characteristics of this transmission line vary with distance along the wire due, for example, to changing distance between the wire and the structure. These changes make it a poor transmission line compared with a coaxial cable. However, the characteristic impedance of a wire over a ground plane changes only logarithmically with the separation distance. This means that the impedance will vary typically by a factor of two or less. It would be difficult to maintain a low VSWR (voltage standing wave ratio) over such a transmission line, but it is good enough for our purposes.

The most straightforward way to use a TDR in checking a hull hardening capacitor is to connect the TDR with clip leads between one terminal of the capacitor and the nearby aircraft structure, as shown in figure 6. The TDR ought to display a short circuit at the position of the clip leads, since for the high frequencies in the TDR's step function, the capacitor is a very low impedance. If the TDR displays something significantly different, there is something wrong with the capacitor or the test setup (i.e., a bad connection). An open circuit capacitor will allow the signal to propagate to the far ends of the wire, so the TDR display will result from a combination of reflections from both directions. The signal may be complex, but should be easily distinguished from a properly installed capacitor.

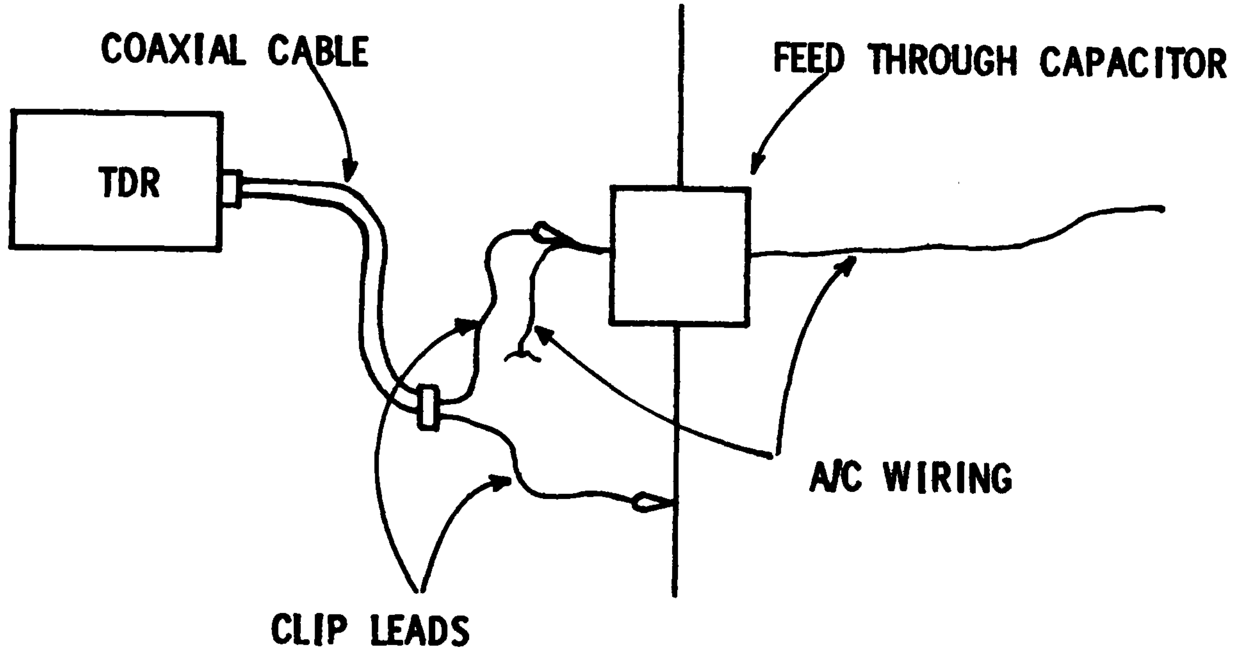


Figure 6. Sketch of Hardening Surveillance Test Using a TDR

SECTION 5

FEASIBILITY DEMONSTRATION

HARDENING SIMULATION

To verify the feasibility of this technique, a simulated wiring harness, ground plane, and EMP hardening installation were built and measurements were made with two TDRs. Each wire was routed along the ground plane, passed through a hole in the plane, and routed along the plane on the other side. Where the wire passed through the ground plane, it was bypassed to ground through a capacitor and a switch. The switch could be opened to simulate an open circuit failure in the capacitor. Various termination impedances were used. The complete circuit is shown in figure 7.

MEASUREMENT SUBTLETIES

Two problems were noted during the demonstration which can easily be avoided in future tests. Most high frequency transmission lines have polarized connectors which allow a TDR to be connected to a circuit in only one way. When using a TDR with clip leads, as proposed here, there is a choice available. While simple theory predicts that the signal reflected back into the TDR by the circuit is the same regardless of the polarization, we found that transposing the clip leads made a significant difference in the displayed waveform. We ascribe this difference to the stray capacitance between the TDR case and the ground plane. When the connections are from the inner conductor to the tested wire and the outer conductor to the ground plane (the "normal" configuration), that capacitance has no effect. However, when the the connections are from the outer conductor of the TDR test lead cable to the tested wire and the inner conductor to the ground plane, the capacitance appears in parallel with the circuit under test.

The other problem was due to the mismatch between the output impedance of the TDR and the characteristic impedance of the test lead cable. This causes multiple reflections of signals, and confuses the displays.

RESULTS

When the TDR is connected directly across a .22 microfarad capacitor, the capacitor appears like a short circuit, as shown in

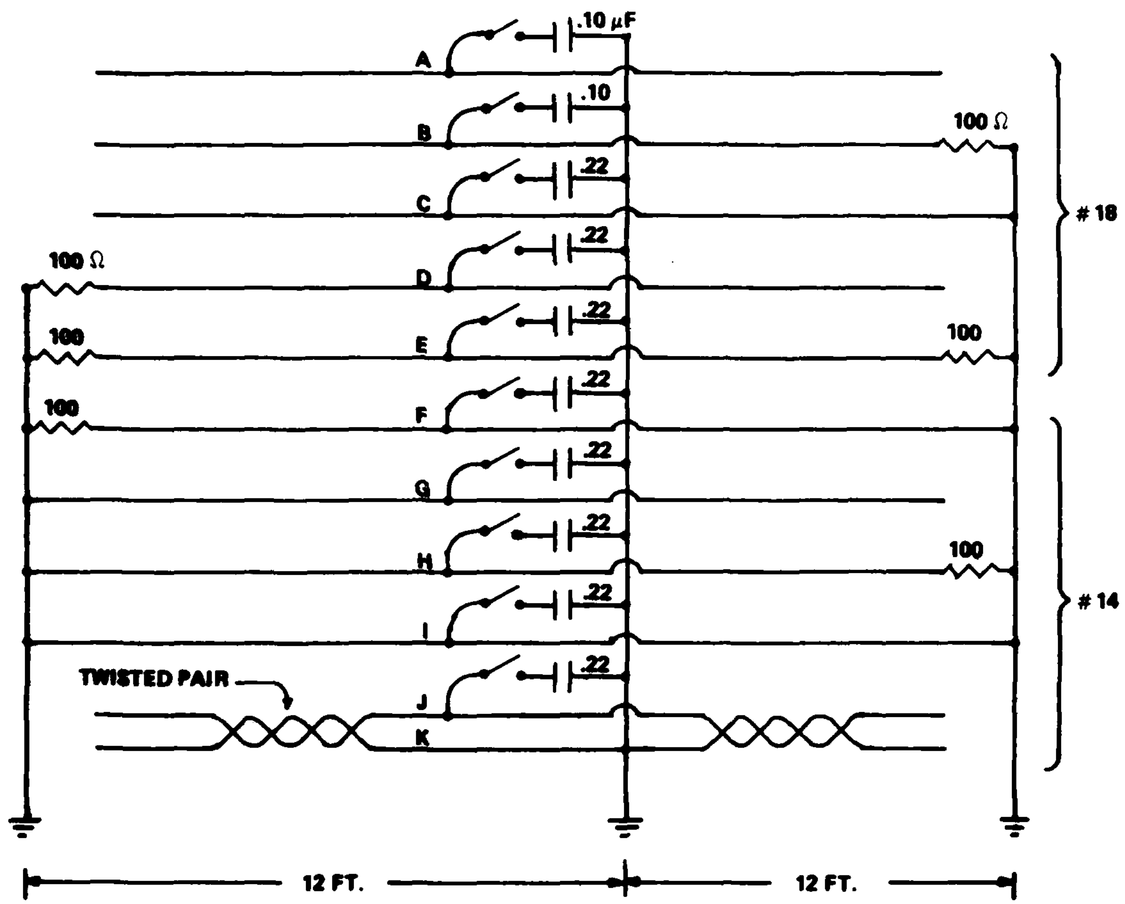


Figure 7. Feasibility Demonstration Circuit Diagram

figure 8. The display is dramatically different if the switch is opened (simulating an open circuit failure), as shown in figure 9. Other termination impedances caused small changes in the display, but the good and bad cases remained easy to distinguish.

One low-pass feed-through filter was tested. The TDR was connected between the filter case and the terminal on each end. The test showed a capacitor between one terminal and the case, and a series inductor between the other terminal and the case. This is consistent with the typical filter circuit, shown in figure 10.

Since the TDR displays the characteristics of a circuit as a function of distance, it can also be connected between one end of the wire and the structure and can determine whether a low impedance exists where the capacitor is supposed to be installed. Measurements made from one end of the wire could distinguish between the good and failed cases, but the differences were much less dramatic than with direct connections (see figures 11 and 12). Apparently, such measurements should not be made unless direct access to the filter is difficult. It would probably be necessary to record the measurements for later comparison.

EQUIPMENT AVAILABLE

We are aware of only three time domain reflectometers: the Hewlett-Packard 1450 and two Tektronix instruments. We were able to make measurements with two of them. The Hewlett Packard TDR is a very flexible laboratory type device. It easily made the desired measurements, but is unfortunately no longer in production. The Tektronix 1502 TDR is designed for measurements in the field. It is portable, can operate off internal batteries for several hours, and with the cover in place is sealed against anything short of being splashed. Tektronix also makes another TDR, the 1503. The 1503 is physically similar to the 1502, but there are electrical differences. The 1503 transmits a single pulse rather than a voltage step, so its display is somewhat more difficult to interpret. It has enough amplitude that measurements can be made on long cables (several kilometers), but has substantially poorer spatial resolution. Since measurements on aircraft would be over very small distances and good resolution would be needed, the 1502 appears to be more appropriate.

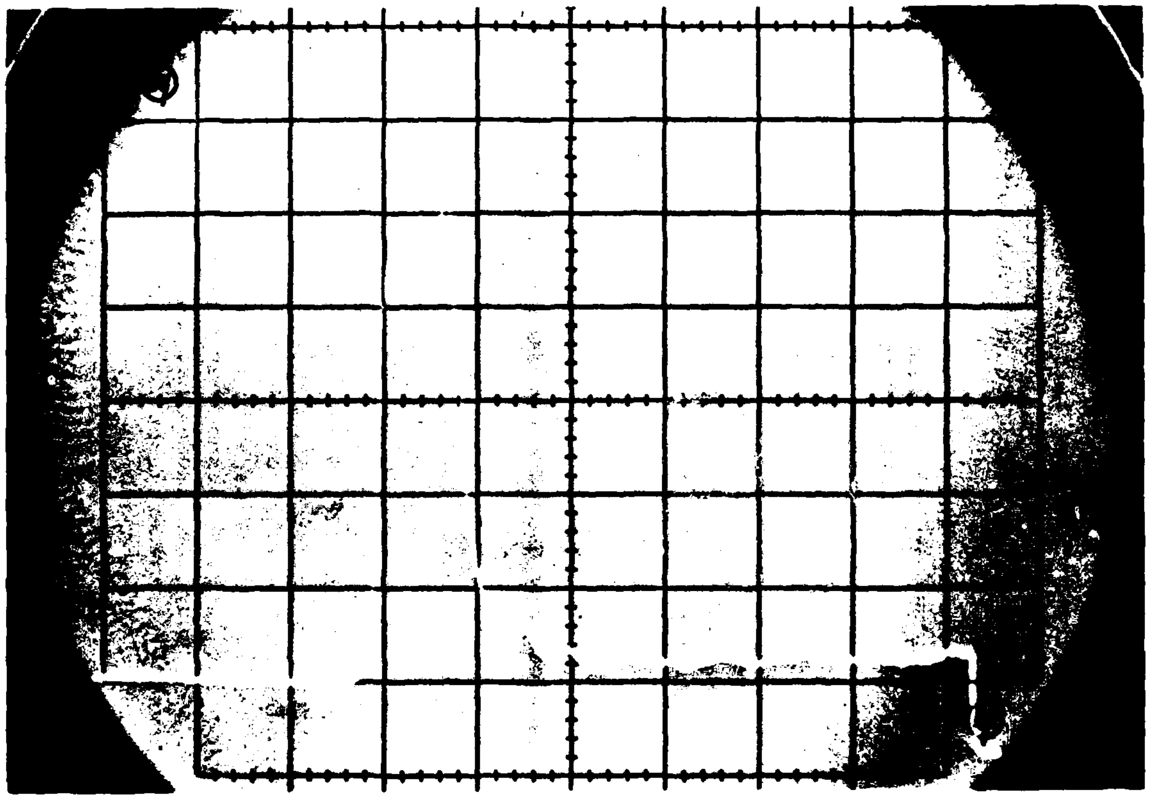


Figure 8. TDR Display, Circuit A, Measurement at Filter Plate, Switch Closed (Good)

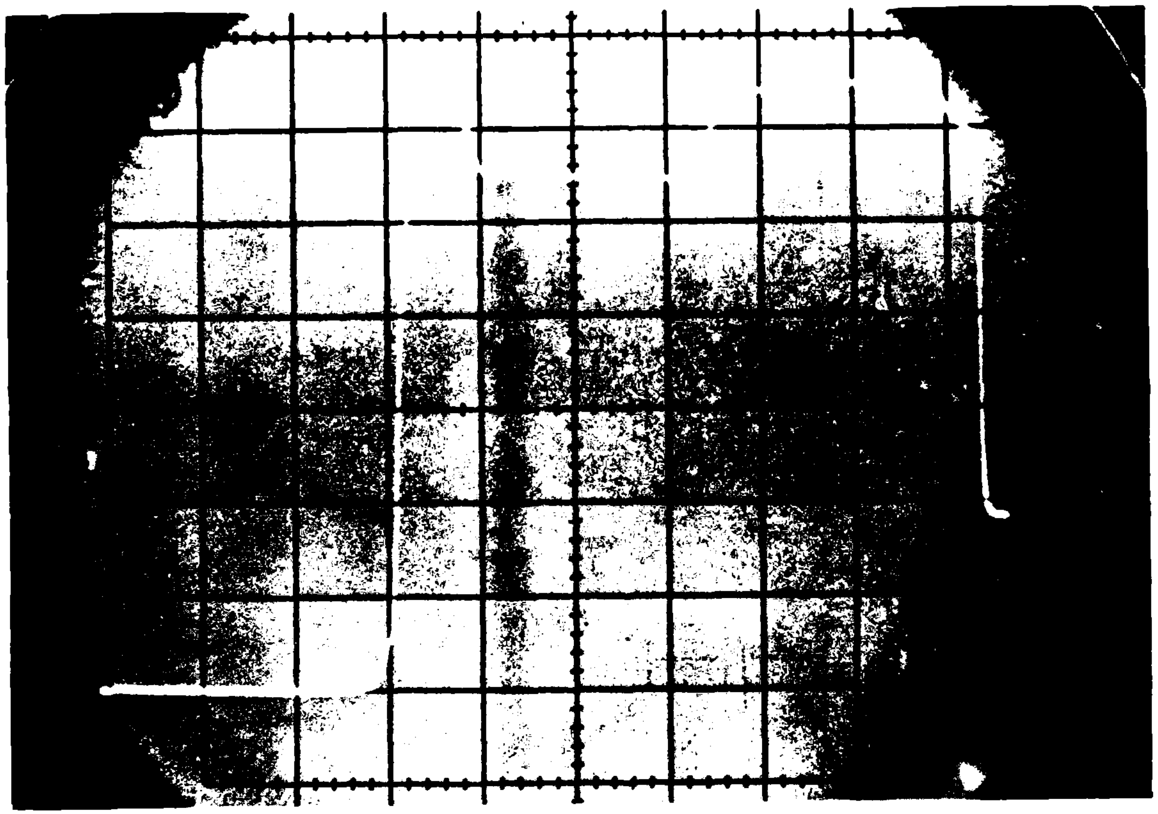
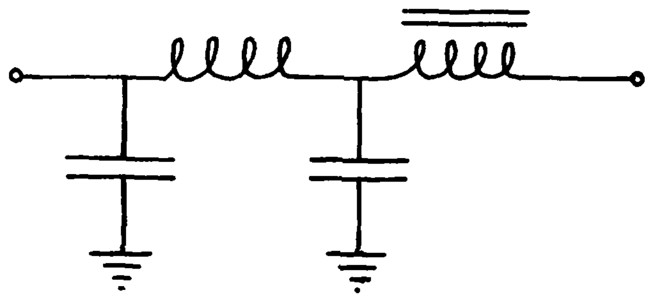


Figure 9. TDR Display, Circuit A, Measurement at Filter Plate, Switch Open (Failed)



"dirty" side "clean" side

Figure 10. Circuit Diagram of Typical LC EMP Filter

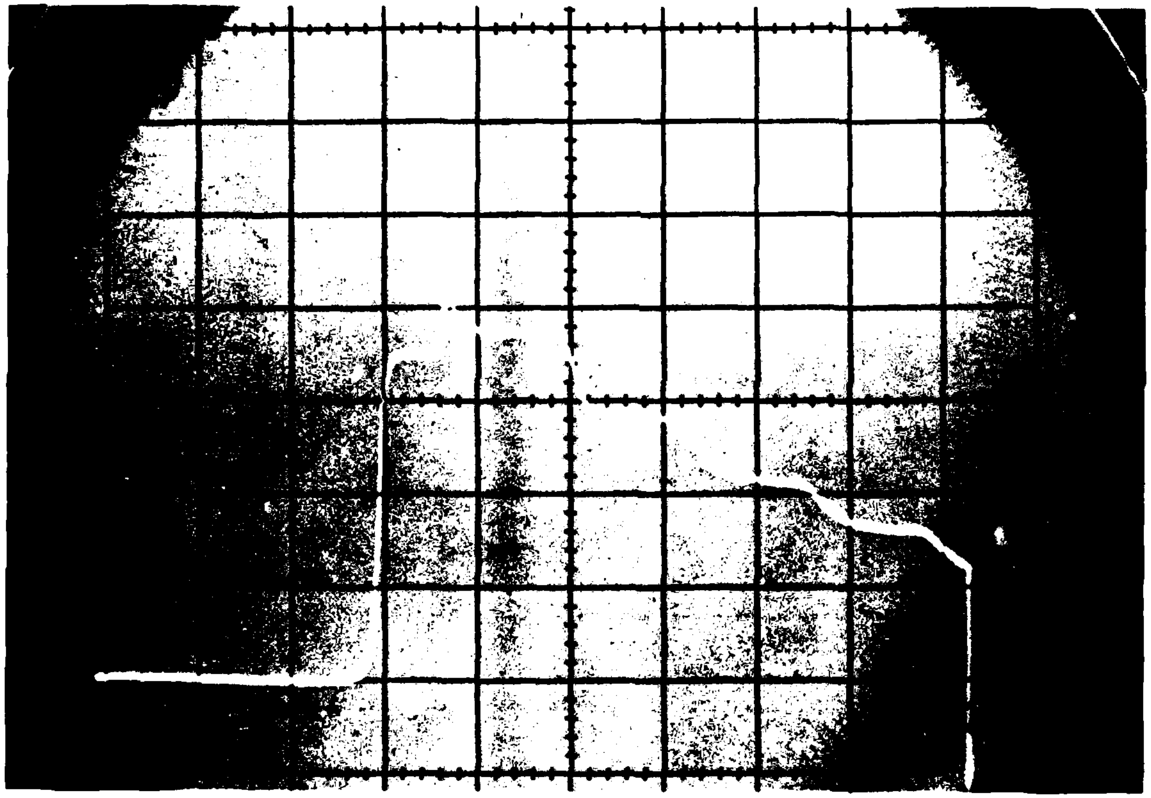


Figure 11. TDR Display, Circuit D, Measurement at Left Hand Termination, Switch Closed (Good)

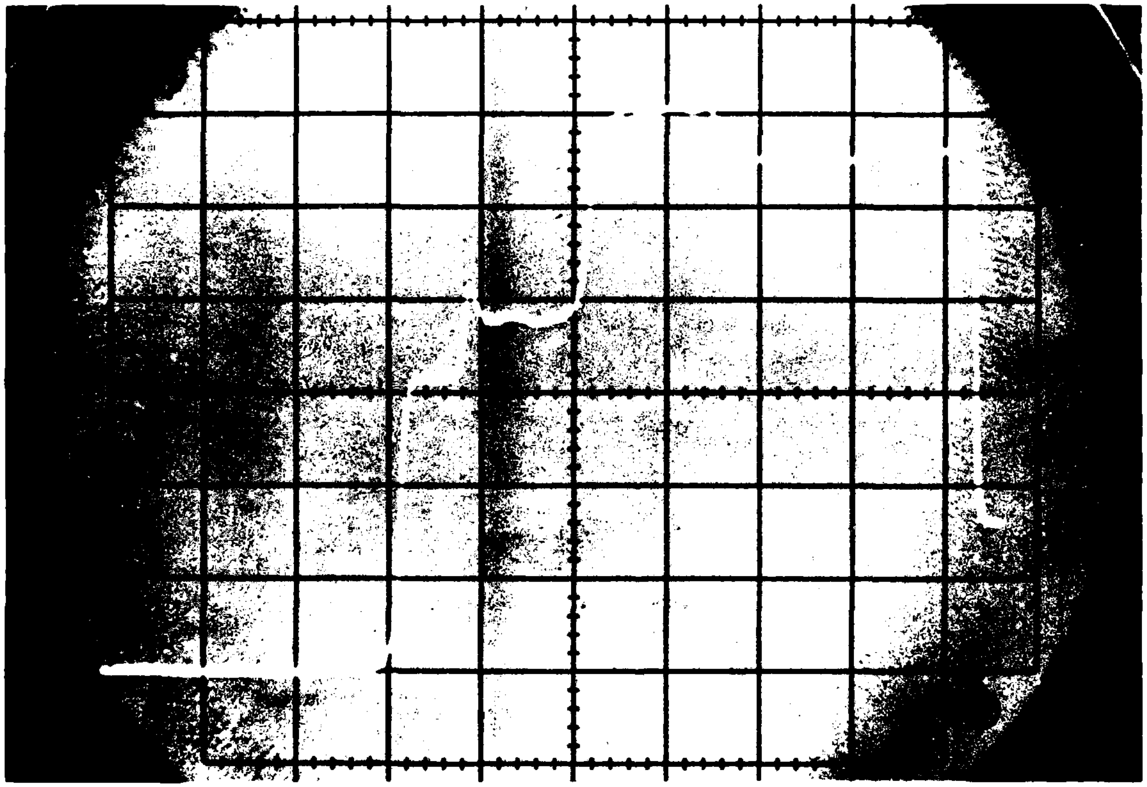


Figure 12. TDR Display, Circuit D, Measurement at Left Hand Termination, Switch Open (Failed)

SECTION 6

CONCLUSIONS AND RECOMMENDATION

The use of a time domain reflectometer to detect open circuit failures in a capacitor has been demonstrated in a laboratory simulation. Measurements made near the capacitor easily detected failures. In measurements made far from the capacitor, the failure could be detected provided records from previous (known good) measurements were available for comparison. The Tektronix 1502 TDR cable tester was found to be well suited to making measurements of this sort in the field.

We recommend that a feasibilit demonstration of this technique be carried out on a hull-hardened aircraft.

REFERENCES

TEK76. "TDR For Cable Testing", Application Note 25M1.0, Beaverton, OR: Tektronix, Inc., 1976.

GLOSSARY

EMP	Electromagnetic Pulse
MHz	Megahertz
TDR	Time Domain Reflectometer
VSWR	Voltage Standing Wave Ratio